Flight Software Implementation of the Beacon Monitor Experiment On the NASA New Millennium Deep Space 1 (DS-1) Mission

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ABSTRACT

A new technology that can lower the cost of mission operations on future spacecraft will be tested on the NASA New Millennium Deep Space 1 (DS-1) Mission. This technology, the Beacon Monitor Experiment (BMOX), can be used to reduce the Deep Space Network (DSN) tracking time and its associated costs on future missions. With BMOX, overall spacecraft health is translated into one of four states. Each of these states is represented by a tone, indicating how urgent it is to track the spacecraft for telemetry. These tones will provide assurances to the ground team that the spacecraft is functioning as expected. In order for Beacon monitor operations to be viable, it is necessary to provide ground operators with concise summaries of on-board events since the last contact. Without these summaries, ground personnel would have to analyze several days of recorded engineering data to understand the events leading to the anomaly. The BMOX data summarization includes a summary of spacecraft anomalies, which are triggered by minimum & maximum limits. These limits and their related data are either pre-defined in a table or defined using envelope functions for more precise selection of the anomaly data. This paper describes the implementation approach of the Beacon monitor experiment on the 11 S- 1 spacecraft, both with and without the Remote Agent autonomous software. The discussion includes an overall description of the Beacon monitor concept, the trade-offs with adapting that concept as a technology experiment, the current state of the resulting implementation on DS - 1, and a description of the validation objectives for the experiment.

INTRODUC'I'1ON

Beacon Technology

The end of the Cold War and the increasing U.S. budget deficit has put pressure on NASA to accomplish more with less money. in the past five years, NASA has been moving towards faster, better, and cheaper missions. Dan Goldin, the NASA administrator, has asked the employees of NASA for new mission operation concepts and new ways of doing business. The Beacon Monitor Experiment (BMOX) is a new technology that can greatly reduce the mission operations cost for deep space missions.

BMOX is a technology experiment involving a spacecraft, a mission-specific ground system, and a set of Earth-based ground stations. in past deep space missions, routine spacecraft health data was relayed to Earth daily via the DSN. Frequent contacts with a spacecraft are costly because they require human interaction and tie up valuable DSN resources that then cannot bc used by other missions. On the other hand, it is important for ground personnel to get spacecraft information frequently so that they can react appropriately. Unfortunately, the DSN personnel are predicting that they will not be able to fully support all currently planned missions with their existing resources. BMOX addresses this problem by changing the way the DSN and mission operations systems operate and interact.

Using the BMOX technology concept, routine spacecraft health data is evaluated on-board the spacecraft. This evaluation results in a simple spacecraft state indication, either Nominal, interesting, important, or Urgent, which can be sent to Earth daily. Each state is represented by a tone, which indicates the level of urgency for contacting the spacecraft for a full heal th status report. Because of their low bandwidth, the state tones can be received by relative] y small (4- 12m) aperture ground stations.

Using BMOX tone monitoring instead of traditional routine ground contacts means that detailed spacecraft performance history is unavailable to ground personnel. BMOX includes a data summarization component that provides this past data in a concise format. There are three different types of summarized data: overall performance summary, user-defined performance summary, and anomaly summary. The performance summaries arc generated at regular intervals and stored in memory until the next telemetry ground contact. They arc computed by applying standard functions, such as minimum, maximum, mean, first derivative, and second derivative, to the data. The data which are summarized are chosen so that the spacecraft state can quickly be determined. User-defined summary data are used for obtaining detailed insight into a particular subsystem and are output at the user's discretion. Anomaly summary data are created when the raw and summarized data violate pre-defined high and low limits. These limits arc determined by the subsystem specialist and stored in a table on-board the spacecraft. The limit tables arc based on the current mission activity. Envelope functions are also used to actively define the limits based on spacecraft performance. BMOX uses the tone generation capability in conjunction with data summarization to fulfill the following five objectives:

- Reduce the frequency of telemetry ground contacts for routine status checks
- Reduce the amount of down-linked engineering data during each ground contact
- Reduce routine ground processing, monitoring, anti analysis of telemetry data
- Schedule DSN antennas based on demand rather than pre-negotiated agreements
- Simplify operations procedures and provide quicker response to anomalies

1) S-1 **Implementation**

Deep Space 1 is the first in a series of advanced technology validation missions defined and implemented as an integrated program for NASA by the Jet Propulsion Laboratory. The main objective of the 11 S- 1 mission is to space-validate a suite of advanced technologies that hold promise for future space science missions with low life-cycle mission cost. The mission profile for 11 S- 1 includes flybys of a near-Earth asteroid, comet, anti Mars.

DS - 1 uses Solar Electric Propulsion (SEP) to drive the spacecraft to its three targets. SEP has a very low thrust level so it must be run almost continuously throughout the mission. In fact, with the exception of the telemetry contacts which off-point the spacecraft from a thrusting attitude, SEP must run for 50 of the first 52 weeks. This SEP continuous "on" requirement increases the importance of BMOX. If there is a problem that shuts down the SEP, it could be up to one week before the ground is contacted via the regularly scheduled telemetry telecommunication pass. This problem would have been handled by the on-board autonomous software Remote Agent (RA), which would have detected the problem, re-configured the spacecraft to solve the problem, anti re-planed the mission using the new configuration.]n March 1997, RA was taken out of the baseline mission plan and replaced with a more traditional mission operations system. This new operations system relies on the ground to build the command sequences and send them to the spacecraft during the weekly telemetry contact. The new system stops the on-board command sequence whenever a major problem is encountered. The SEP system is shut down as well. With J3MOX enabled, the SEP shutdown could be detected in less than a day. Without BMOX, the ground personnel must wait until the next scheduled telemetry contact to get a spacecraft status report.

Summarization is also important to a mission with weekly ground contacts. Many events can occur between ground contacts. The spacecraft has the capability to store telemetry during this time but if there is a problem, it could take days to sort through the data to find the cause. Summarization capability can help by giving ground personnel a concise history of spacecraft anomalies since the previous contact.

FLIGHT SOFTWARE OVERVIEW

The Beacon Monitor Software (BMS) is part of the 11 S- 1 flight software (FSW). We have implemented BMS as a VxWorks task to be run on the 1] S- 1 flight processor. BMS receives inputs from the ground and from other FSW modules via the 11 S- 1 Inter-Process Communication (IPC) services, and produces output via the same medium. Every internal table is implemented using a generic architecture that can be applied to future missions. BMS can be turned off, on, and reset with an IPC message. Normally, this message would be sent via a command from the ground or the on-board command sequence.

TONE SEI,IKW1ON SOFTWARE

A design philosophy of the 11 S- l project is to separate BMOX from the other flight software as much as possible. This philosophy evolved from the fact that Beacon is an experiment that should not interfere with other spacecraft subsystems. Although this philosophy has posed some significant design challenges, it makes the software easier to test and easily adaptable to future spacecraft. The design challenges have primarily involved the interface between Beacon and the fault protection software. When the RA software was included in the design, a task called Mode identification and Recovery (MIR) handled the fault protection duties. MIR would use information provided by the Smart Executive and monitors to determine the spacecraft state. M IR would pass the spacecraft state to the Beacon software, which in turn would map that state to a Beacon tone. After the RA was removed from the baseline plan, the fault protection design has been based on the Mars Pathfinder Spacecraft fault protection. We arc in the process of designing the interface between the Beacon software and the new fault protection and will describe our thoughts on the design later in this section.

The Beacon tone can bc one of four different states: Nominal, Interesting, Important, and Urgent. Each state represents the urgency of communicating with the spacecraft for a status check. A fifth state in which no tone is received when one is expected is also possible. The tones are defined in Table 1. While the Beacon tone is enabled, the telecommunications system will continuously transmit a representation of the Beacon tone by modifying the sub-carrier frequency of the transponder. For a detailed description of the telecommunications system related to BMOX, see reference [1]. BMOX software will not allow the Beacon tone to bc changed to a less urgent state unless a reset command is sent from the ground. This prevents the ground from missing a higher urgency tone should a lower urgency tone follow.

TONE	DEIONITION	EXAMPLES
Nominal	Spacecraft is nominal; all functions are performing as expected. No need to downlink engineering telemetry.	. Spacecraft operating normally
Interesting	An interesting and non-urgent event has occurred on the spacecraft. Establish communication with the ground when convenient to obtain data relating to the event.	. Device reset to clear error caused by Single Event Upset . Other transient events that do not repeat
Important	The spacecraft needs servicing. Communication with the ground must be achieved within a certain time or the spacecraft state could deteriorate and/or critical data could be lost.	. Solid state memory near full . Non-critical hardware failure
Urgent	Spacecraft emergency. A critical component of the spacecraft has failed. The spacecraft cannot autonomously recover and ground intervention is required immediately.	. Spacecraft bus failure . Power Distribution Unit failure • Star Tracker failure . Ion Propulsion System gimbal stuck
- No **Tone** -	No Beacon Tone was received by the ground station at the scheduled time.	• Beacon software is not operating • Anomaly prohibited tone from being sent • Spacecraft destroyed by meteor . Ground system problem

Table 1 Beacon Tone Definitions

The current design of the Beacon software uses two methods to set the Beacon tone. interesting and Important messages are generated when the episode identifier (EI) module of the Beacon software starts an episode. The EI module is described in greater detail later.

Urgent Beacon tones are set by the spacecraft fault protection when standby mode is entered. This condition occurs when the fault protection encounters a fault that it cannot correct. Standby mode halts the current command sequence, including SEP thrusting. The operational margin for SEP thrusting at launch based on current mass and power estimates is two weeks (plus eight hours per week since launched.) This margin represents the duration for which SEP could be off and still allow the spacecraft to reach both the asteroid and the comet. During the second half of the primary mission, DS-1 only communicates with the ground once per week. A single standby mode could conceivably last several days. The project engineers are concerned that one or two standby modes could usc up all of the SEP operational margin so they have asked the BMOX team to investigate using the Beacon tones to notify the ground in case of standby mode.

Several scenarios have been investigated for operating the Beacon tone during the primary mission. All scenarios involve transmitting the Beacon tone at a prescheduled time on a regular basis, i.e. 30 to 60 minutes per day. The Beacon tone is not operated continuously because DS - 1 requires as much power as possible for SEP thrusting. One possible scenario is to transmit the urgent tone for the first 24 hours of standby mode and then switch to low rate telemetry. This would ensure that the Beacon tone was retrieved during the scheduled daily Beacon track. One problem with this scenario occurs if the 24 hours of Beacon tone broadcast coincides with the regular 8-hour weekly telemetry pass. In this situation, the ground would be expecting telemetry but would receive the Beacon tone. Another possible scenario for detecting standby mode involves alternating the Beacon tone and telemetry during standby mode. The time that each would be on would depend upon the time needed to acquire telemetry at the ground station. The most likely option that serves the needs of the DS- 1 project uses the Interesting and important tones during the regularly scheduled Beacon contacts. 'l'he urgent tone would be replaced by standard spacecraft telemetry. In this case the Beacon team would not detect a tone and eventually look for standard telemetry. This design gradually phases in BMOX while providing assurances to the project that telemetry can be received in an emergency. Wc plan to use this mode of operation after the asteroid encounter. The cruise to the comet encounter will be used to verify the operation of BMOX.

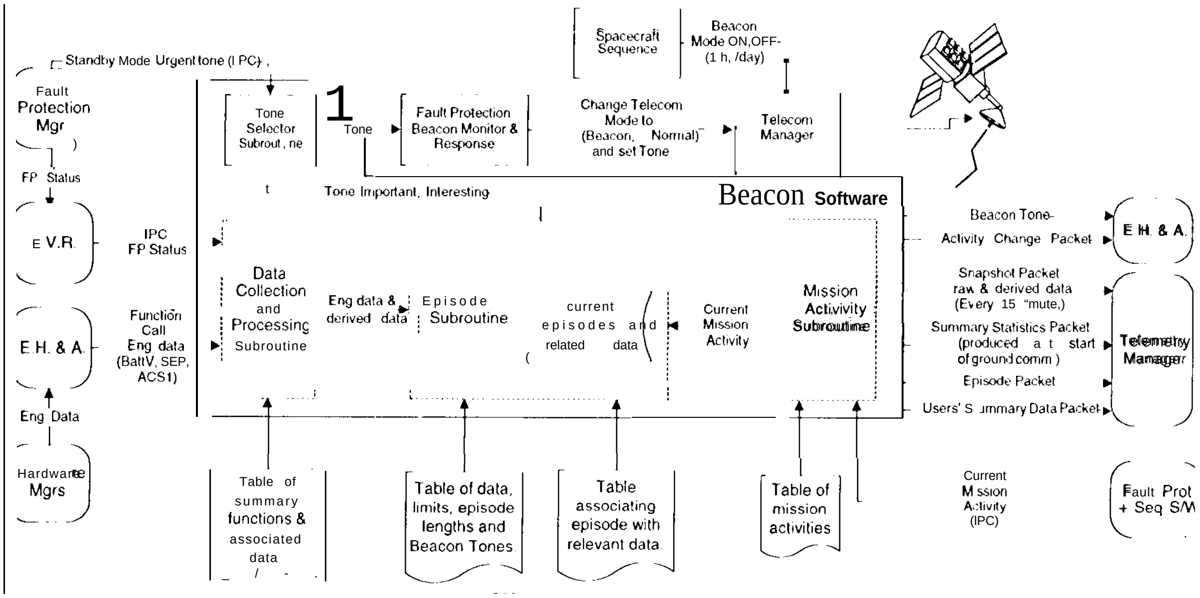

Figure 1 Beacon Software Inputs and Outputs

'l'one Selector Internal Operation

At start-up, and each time the tone selector software (Tonesel) transitions from the OFF state to the ON state, it publishes a current tone message and a telemetry packet reporting the current setting of the Beacon tone. The fault protection to Beacon interface receives this message and commands the telecommunications system to transmit the Beacon tone if tone generation is enabled. A flow diagram showing these interfaces is contained in Figure 1. When Tonesel is started for the first time or reset, a nominal tone message will be generated. When Tonesel receives an off message, it stops mapping faults to Beacon tones, but retains the current setting of the Beacon tone.

Current Status

Tonesel was functionally complete for the original 11 S- 1 flight software configuration. We will be modifying Tonesel to conform to the new fault protection software, the new inter-process communication services, the new timing services, and the new telemetry services.

DATA SUMMARIZATION

The data summarization part of BMOX is vital to the Beacon operations concept. Without it, if an Urgent tone is received and the ground has not communicated with the spacecraft for several weeks, ground personnel would need to analyze vast quantities Of paSt recorded data. This scenario assumes that the spacecraft has the capacity to store the data. Summarization gives the ground personnel a quick look at spacecraft activity since the previous ground contact. With summarized data, ground personnel will be able to rapidly identify the causes for the Beacon tone and take corrective action to avoid further problems.

Summarization Internal Operation

The Summarization/Sampler Module (Sampler) begins in the OFF state, with all summarization values zeroed out. First, Sampler reads an initialization file containing definitions of each raw data item to be received, every summarization formulae to be applied, all data limits to be checked, and every user summary packet to be produced.

Telemetry Name	Description	Output Frequency
Activity	Documents the changes in mission activity as detected by Sampler.	One packet is produced each time the activity changes
Data Sample	Records a snapshot of every raw and summarized data channel col lected by Sampler.	Regular interval, e.g., 15 minutes
Episode Summary	Records general data about an out-of-limits data condition, known as an "episode."	One per episode
Episode Channel	Records speci fic dat a about a single data channel's behavior during an episode.	Onc or more per episode
Value Summary	Records summary data about a single data channel's behavior since the last downlink.	One for each channel out of limits since the last downlink
User Summary	A Llser-specified packet containing raw and/or summarized data previously specified by the user.	Duration specified by the user

Table 2 Summarization Telemetry Packets

Once the initialization file is read, Sampler waits for message input via function calls from the engineering telemetry module (EHA). Sampler also receives mission activity updates via an IPC message that it uses to determine which summary calculations and data limits to apply. All of the Sampler interfaces can be seen in Figure 1. 'The different telemetry packets published by Sampler arc listed in Table 2.

Episode Identification

An essential element of summarization processing is the "episode." An episode, for BMOX purposes, is a 10-minute period that begins 5 minutes before any monitored data channel goes out of limits. When an episode starts, the Interesting or important tone message associated with the out of limits channel is sent to the tone selector module. Only one episode can be in progress at a time; all data channels that go out of limits during that time are recorded as part of the episode. An episode is always ten minutes long, even if all channels return to within limits before the end of the episode, with one exception: If the mission activity changes during an episode, the episode is ended immediately. If any channel is still out of limits when the episode ends, another episode is begun. Termination of an episode produces an episode summary packet and episode channel packet(s). The summarization process is run once per second.

ELMER Limit Checking

In an episode, the method of anomaly detection is limit checking, in which the current sensor value is compared against predetermined high and low "red-lines." Determining tight limits, which will be valid throughout an entire mission, is a difficult task. Thus, to avoid frequent false alarms, the red-lines are made imprecise, which could lead to missed alarms and missed opportunities for early anomaly detection.[2] Several alternatives to basic limit checking have been examined for addition to the 1) S- 1 Summarization software.

One alternative to limit checking is discrepancy checking, which examines the difference between the actual sensor value and a predicted value determined through simulation. Because the simulation uses knowledge of the current spacecraft state in the prediction, the bounds will be much tighter than the red-lines, leading to significantly fewer missed alarms. However, due to inherent imprecisions in the simulation model, discrepancy checking would be overly precise, producing an unacceptable number of false alarms. [3]

This historical knowledge of the spacecraft can also be used to generate high and low envelopes of valid sensor values. The use of high and low bounds is similar to the red-lines used in limit checking, but instead of static constants, these generated envelopes are dynamic functional limits based on the current sensor and other factors, such as the values of other sensors and the spacecraft's operational mode. This is the approach that the ELMER (Envelope Leaning and Monitoring via Error Regression) algorithm takes. [2]

Running ELMER with a single sensor as input will produce high and low red-lines which reflect the expected maximum and minimum values of the sensor. Further iterations of the algorithm, adding sensor dependencies and lag vectors, will incrementally tighten the envelopes. As a rule, ELMER rejects any bound which causes alarms in nominal training data, therefore avoiding the problem of increased false alarms that occurs with tighter red-lines. Provided the historical data is representative of the sensor's nominal values, the envelopes will be loose enough to avoid false alarms (as red-lines arc), but tight enough, due to the training, that fewer alarms will be missed and anomalies will be detected sooner (as in discrepancy checking). [2, 3]

For BMOX, ELMER will be used to generate the high anti low envelopes that will be used to test whether an anomaly has occurred and the Beacon tone should change. ELMER is being tested on the ground with historical data from NASA's TOPEX mission.

Current Status

With the exception of the adaptive calculation of data limits, Sampler was functionally complete for the original DS- 1 flight software configuration. Adaptive limits will be added before final delivery of the software. In addition, under the original configuration tone commanding was only done by Tonesel in response to health state messages received from the Remote Agent. Under the new configuration, Sampler is responsible for sending SET_TONE commands to Tonesel. Sampler will be modified to do so, and also to conform to the new interprocess communication services, the new timing services, and the new telemetry services.

VALIDATION OBJECTIVES

A series of experiments for BMOX arc used to validate the Beacon technology. There arc five validation objectives for BMOX:

- Engineering summary data generation and visualization
- Tone (state) selection
- Tone generation, transmission & detection
- Ground support including message handling & reporting, and DSN track scheduling
- Operations effectiveness assessments

The majority of these objectives can be achieved within the first three months of the mission. The overall goal is to demonstrate the end-to-end system of tone selection, detection, and scheduling the DSN for a demand access telemetry pass.

CONCLUSIONS

The BMOX concept is a major paradigm shift from the standard mode of spacecraft operations. The Deep Space Network does not have the resources to support the numerous smaller missions planned for the years ahead. BMOX is an enabling technology for these better, faster, and cheaper deep space missions. Although the DS- 1 mission has changed from an autonomous spacecraft to a more traditional system, the Beacon software has evolved to meet the needs of DS - 1 and future missions.

ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Specifically, the BMOX experiment is funded by the NASA Autonomy and information Management Program, the MGSO Continuous Improvement Program, and the TAP Advanced Technology Program.

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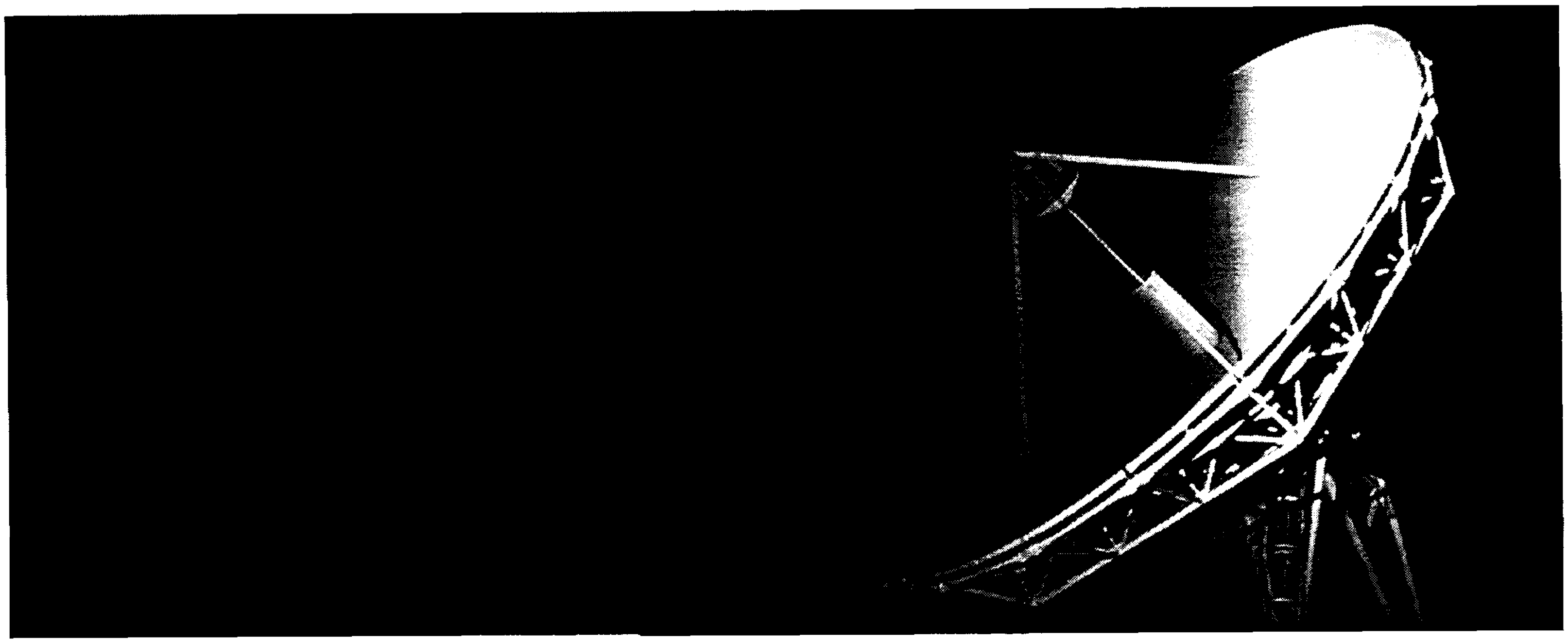


Symposium on Reducing the Cost of Spacecraft Ground Systems and Operations

Keble College, Oxford

22 July 1997

JPL

Topics

- Beacon Monitor Technology
- DS-1 Mission Beacon Monitor Experiment (BMOX)
- Components
  - Tone Monitoring System
  - Engineering Data Summarization
- Design Considerations & Lessons Learned
- Key Innovations

Origins of the Beacon Concept

- Need to reduce ops. cost for future missions

- Arose out of Goldin's vision of "darkening the skies"
  - Need to reduce loading on DSN antennas
  - Need to reduce the size of ops staffing and complexity of operations

- New Millennium Program
  - Selected as a Deep Space One (DS-1) Flight Experiment

Objectives [Tone Selector]

Technology Objective:
- Reduce frequency of tracking for routine engineering telemetry

Advantages:
- Reduces the loading on ground antennas
- Reduces workload on operations team

Approach:
- Replace telemetry with a signal that provides assurance of spacecraft health but is detectable with simpler [and lower cost] ground resources

Objectives [Data Summarization]

Technology Objective:

- Reduce the amount of downlinked engineering data per telemetry pass

Advantages:

- Enables more missions to be supported
- Reduces the duration of telemetry passes
- Reduces workload on operations team

Approach:

- Provide reusable software modules to perform engineering data summarization above the state-of-the-art

Objectives [Automated Scheduling]

Technology Objective:

- Schedule DSN tracking based on demand rather than pre-negotiated agreements

Advantages:

- Saves DSN operations costs by automating DSN antenna scheduling process

Approach:

- Use automated scheduling software to perform spacecraft-initiated scheduling of DSN antennas

Objectives [Overall]

Technology Objective:

- Simplify Ground Operations

Advantages:

- Reduce size of ops team to lower mission cost
- Better allows ops teams to support multiple simultaneous missions

Approach:

- “Automate tone message handling & reporting
- Add capabilities for visualizing summary data
- Send tone continuously to avoid scheduling tone tracks
- On-demand spacecraft engineering teams

Deep Space One Spacecraft (DS-1)

- Part of New Millennium Program whose main objective is to flight validate new technologies
- Mission includes flybys of an asteroid, Mars, and a comet
- Beacon technology selected as an experiment
- Can be used to enhance primary mission:
  - Can minimize loss of SEP thrusting
  - DSN station DSS-26 is an added mission resource
  - Summary data will be made available to operators

Solar Electric Propulsion on DS-1

- SEP is used to drive DS-1 to its three targets
- SEP must be run almost continuously during the primary mission to reach targets
- DS-1 Fault Protection software disables SEP after detecting most anomalies
- DS-1 will use weekly telemetry downlinks
  - could be up to a week before ground personnel realize that SEP has been disabled
  - with BMOX enabled, this time could be cut to 1 day

Tone Selection - I

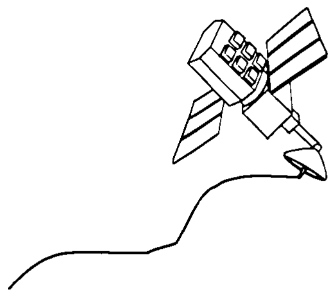
NOMINAL	All functions are performing as expected. No need to downlink engineering telemetry.
INTERESTING	Establish communication with the ground when convenient to obtain data relating to an event. Examples: device reset due to SEU
IMPORTANT	Spacecraft needs servicing within a certain time or spacecraft state could deteriorate or critical data could be lost. Examples: solid state memory near full, non-critical hardware failure
URGENT	Spacecraft emergency. A critical component has failed. The spacecraft cannot adequately recover. Ground intervention is required immediately. On DS-1, set by Fault Protection after entering "standby" mode.
No Tone	Beacon mode is not operating, telecom is not earth-pointed, or a spacecraft anomaly prohibited tone from being sent.

Tone Selection - II

- Missions determine mapping of spacecraft state to urgency of ground response
- Mapping resides in a simple look-up table on-board the spacecraft
- Beacon tone cannot transition to a lower state unless reset by a ground command

p..... Tone Detection

- Goal is to use a small (4-12m) aperture antennas
  - DS-1 will be using DSS-26 (34m)
  - We may also use the Naval Academy 12m station
- Detection time is around 15 minutes
- Tones are spaced to minimize detection uncertainty introduced by:
  - Oscillator noise
  - DFT frequency spread
  - Doppler



Data Summarization: Transforms '

- Transforms in DS-1 Architecture
  - Minimum, maximum, mean, 1st Derivative, 2nd Derivative
  - Combinations of the above functions
- Minimum, Maximum and Mean are efficient ways to summarize nominal data
- Using transforms to identify episodes
  - Mean enables detection based on length of time above or below a threshold
  - 1st and 2nd Derivative allow detection when a an oscillating signal fails to change but is still within the nominal alarm thresholds (1st & 2nd derivative= 0)

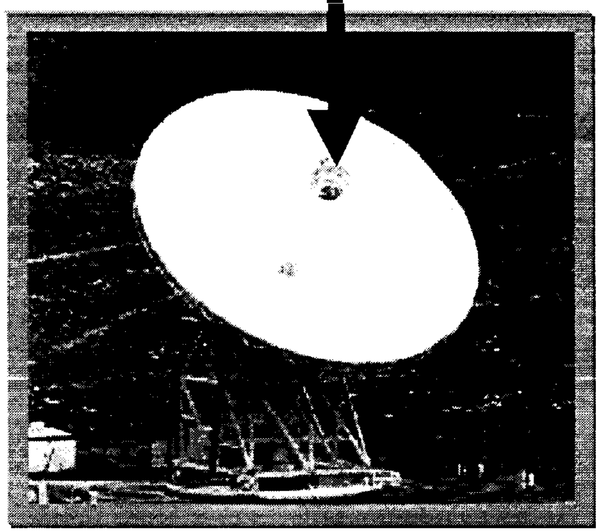
Summarization Output Data

Telemetry Type	Description	Output Frequency and Duration
Activity	Documents changes in mission activity, i.e. maneuver, downlink, SEP thrusting, etc.	One packet is produced each time the activity changes
Data Sample	Records a "snapshot" of every raw and summarized data channel	Regular interval (e.g. 15 min), scales with mission distance
Episode Summary	Records general data about an out-of-limits data condition	One per episode
Episode Channel	Records specific data about a single data channel's behavior during an episode	One or more per episode
Value Summary	Records summary data about a single channel's behavior since the last downlink	One for each channel out of limits since the last downlink
User Summary	A user-specified packet containing raw and/or summarized data previously specified by the user	Duration specified by the user

Engineering Data Summarization

Prioritized Downlink

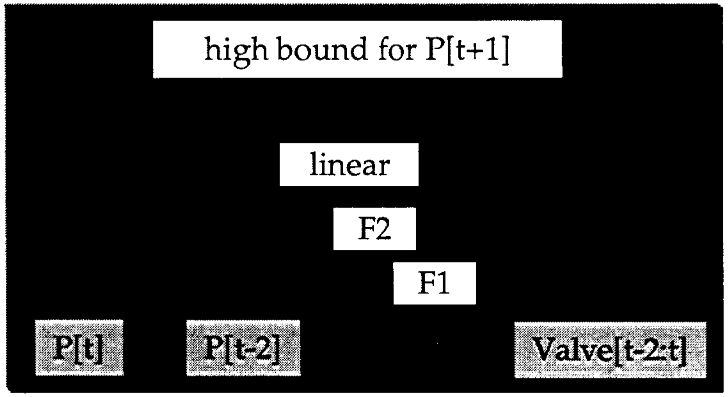
- Special Performance Data
- Summary of Nominal Data
- Episode Data
- Top-level Summary



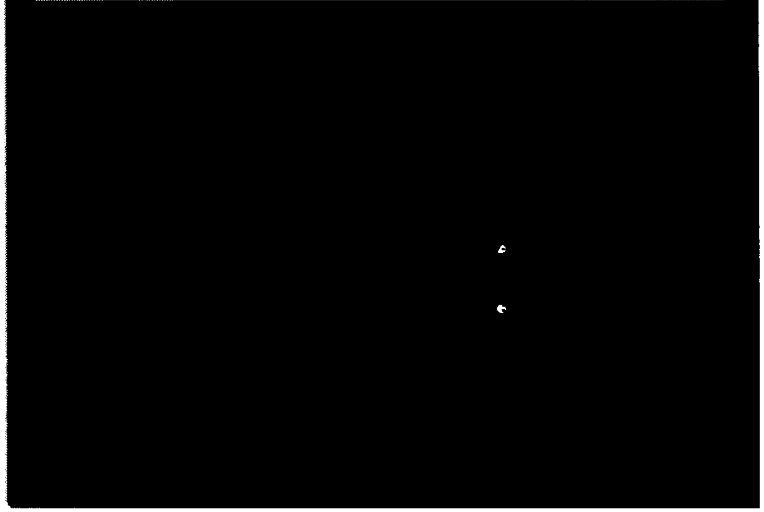
Adaptive Alarm Thresholds

Concept

- Adaptive filtering approach
- Alarm thresholds are learned by training a neural net on <u>nominal</u> engineering data
- Ground-based training



ELMER: Envelope Learning and Monitoring using Error Relaxation



Major Advantages

- More precise episode identification for summarizing engineering data
- More accurate anomaly detection

DS-1 Implementation

- Summarization architecture can be configured to use hard-coded limits or adaptive limits for episode identification
- Adaptive limits not linked to spacecraft fault protection

Spacecraft Design Considerations

- On-board storage
- Telemetry management architecture
  - Should be capable of prioritizing downlink
- Pointing requirements
  - To secure tone link
  - Must know situations when off earth-point
- Power
  - Continuous tone transmission enables tone tracks to not be scheduled
  - Transponder power directly affects ground antenna size

lessons learned: DS-1 Development

- Architecture is adaptable to both highly autonomous and more rudimentary flight systems

- Spacecraft design must reflect beacon monitoring requirements early
  - Pluto Express example
  - DS-1 severely power constrained

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- Operational risks associated wtih "Darkening the skies" approach not yet endorsed by all project engineers at JPL

Summary of Validation Objectives

Beacon Tones

Generation - demonstrate correct mapping of spacecraft state to tone state

Transmission & Detection - demonstrate an end-to-end tone system

Engineering Summary Data

Generation - demonstrate that summaries are accurate reflections of onboard conditions

Visualization - demonstrate efficient methods for viewing engineering

Multi-mission Ground Support

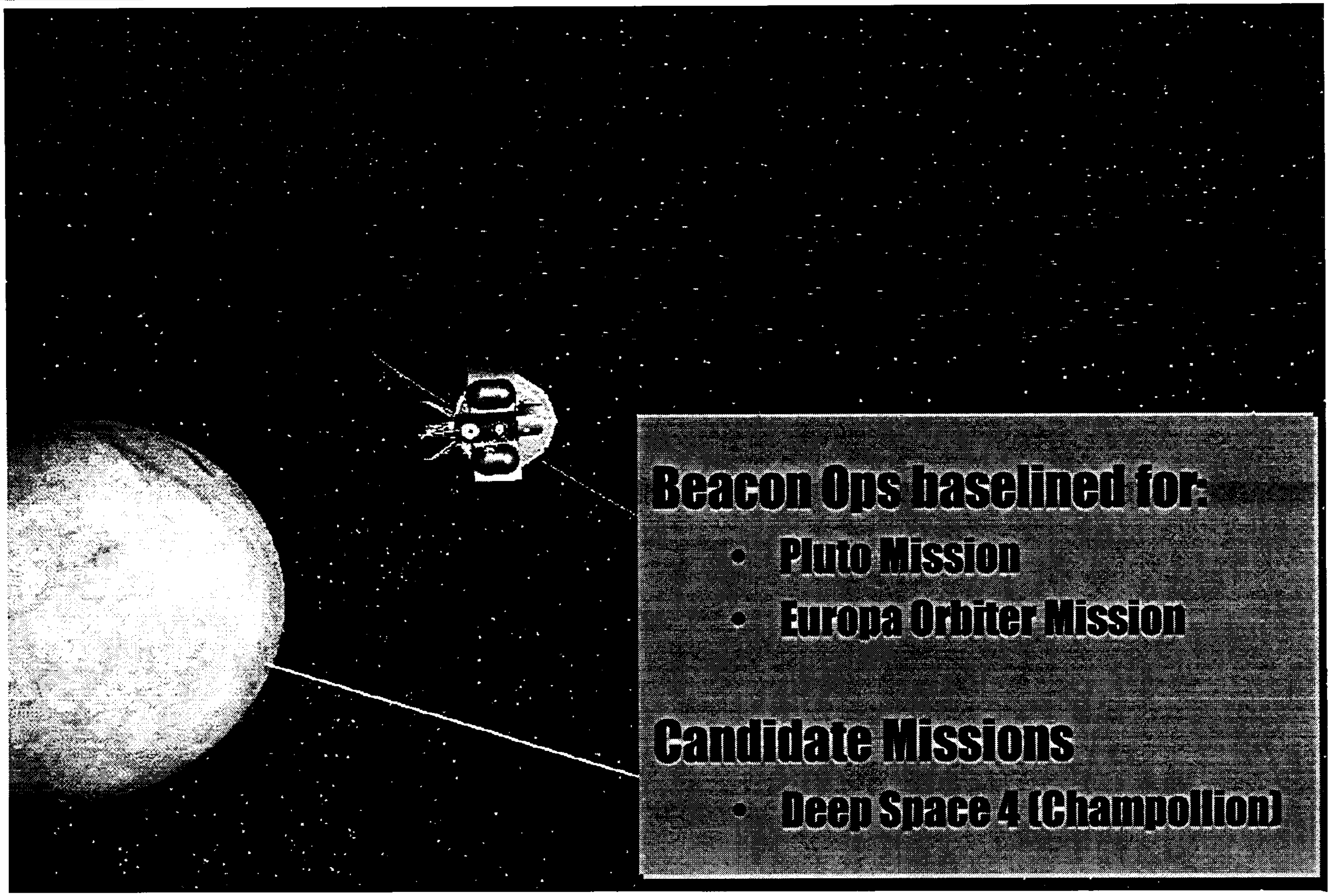
Tone message handling & reporting - demonstrate a low-cost process for relaying tone state to the flight team

DSN track scheduling - demonstrate viable demand-based scheduling of DSN antennas for telemetry tracks

Operations Concept

Verify that beacon monitor operations can reduce flight project operations cost and reduce the loading on DSN antennas

Future Beacon Customers



Key Innovations

Innovation	Rationale
Four levels of urgency in tone signalling system	Maps most cleanly into ops decision space
Suite of techniques for on-board engineering data summarization	Needed for fast response and solves bandwidth limitations
Advanced Scheduling software	Supports demand-based scheduling of telemetry tracks
Automated tone message handling & reporting	Shortens response time

Acknowledgements

INNOVATORS

- John Carraway
- Bruce Crow (ret.)
- Richard Doyle
- Jay Wyatt

SPONSORS

- NASA Autonomy and Operations Program
  Mel Montemerlo - NASA HQ
- PL Multi-mission Ground Systems Office Continuous Improvement program
  Bob Wilson - JPL Program Element Mgr.
- JPL Telecommunications and Mission Operations Directorate Advanced Development Program
  Chad Edwards - JPL Program Mgr.

Flight SW Architecture

Summary Results